

2001 QR₃₂₂ – an update on Neptune’s first unstable Trojan companion

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Summary: The Neptune Trojans are the most recent addition to the panoply of Solar system small body populations. The orbit of the first discovered member, 2001 QR₃₂₂, was investigated shortly after its discovery, based on early observations of the object, and it was found to be dynamically stable on timescales comparable to the age of the Solar system.

As further observations were obtained of the object over the following years, the best-fit solution for its orbit changed. We therefore carried out a new study of 2001 QR₃₂₂’s orbit in 2010, finding that it lay on the boundary between dynamically stable and unstable regions in Neptune’s Trojan cloud, and concluding that further observations were needed to determine the true stability of the object’s orbit.

Here we follow up on that earlier work, and present the preliminary results of a dynamical study using an updated fit to 2001 QR₃₂₂’s orbit. Despite the improved precision with which the orbit of 2001 QR₃₂₂ is known, we find that the best-fit solution remains balanced on a knife-edge, lying between the same regions of stability and instability noted in our earlier work. In the future, we intend to carry out new observations that should hopefully refine the orbit to an extent that its true nature can finally be disentangled.

Keywords: Neptune Trojans, Solar system formation, Solar system evolution, Centaurs, Comets, 2001 QR322, Dynamical Methods

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Introduction

In 2001, astronomers carrying out the Deep Ecliptic Survey ([36][37]) announced the discovery of five new trans-Neptunian objects, including one given the designation 2001 QR₃₂₂. In the discovery circular [1], the proposed orbit for that object would have made it a Plutino (e.g. [2][3]), trapped in Neptune’s 2:3 mean-motion resonance. Indeed, the circular states: “*The assumed perihelic Neptune 2:3-resonance orbit for 2001 QR322 keeps the object more than 16 AU from Neptune over a 14 000-year period*”.

As a Plutino, 2001 QR₃₂₂ would not have been particularly remarkable – well over a hundred have been found to date. However, it was soon realised that 2001 QR₃₂₂ was significantly more interesting. Follow-up observations in November and December 2002 led to major revisions in the best solution for the objects orbit, and in January 2003, it was announced that 2001 QR₃₂₂ was, in fact, a Neptune Trojan – the first to be discovered [4]. In that circular, it

was noted that, “[a]ccording to the above orbit, the 1:1 Neptune liblator remains more than 20 AU from Neptune over a 14 000-year period. E. Chiang has confirmed the object's status as the first known "Neptune Trojan" by integrating the orbit over 10^9 years”.

Following up on the discovery, two independent studies examined the orbital stability of the newly detected Neptunian Trojan. [5] employed a Frequency Map Analysis to produce maps of the diffusion rate of hypothetical Uranian and Neptunian Trojans. They noted that 2001 QR₃₂₂ lay close to the border of a stable region for low inclination Neptune Trojans, but found its orbit to be highly stable. They performed numerical integrations of a population of test particles based on the best-fit orbit of 2001 QR₃₂₂, and found that only 10% escaped from the Trojan cloud over the lifetime of the Solar system, inferring that the object must be primordial, rather than a recent capture.

This result was strongly supported by the work of [6], who found that whilst the orbital evolution of 2001 QR₃₂₂ within the Neptunian Trojan cloud was chaotic, perturbed by the ν_{18} secular resonance, this was insufficient to cause the object to escape from the Trojan cloud. In their simulations, the authors found that “[t]he probability of escape to a non-Trojan orbit in our simulations was low, and only occurred for orbits starting near the low-probability edge of the orbital element distribution (largest values of initial semimajor axis and small eccentricity)”. The stable nature of 2001 QR₃₂₂, it seemed, was confirmed, and was thereafter assumed by studies considering the formation and evolution of the Neptunian Trojan population (e.g. [7][8]).

In 2009, we began a project to examine whether it was possible to use the distribution of the Neptune Trojan population to constrain the nature of the giant planet’s outward migration. It was clear from the orbits of the Plutinos that Neptune must have migrated over a considerable distance (e.g. [9][10]), but the newly discovered Neptune Trojans offered the opportunity to test the models of planetary migration to see which, if any, could reproduce the observed distribution, and predict the range of orbits over which future Trojans would be found (e.g. [11][12][13][14]).

In the course of that work, we noticed that the best-fit orbital solution for 2001 QR₃₂₂ had changed significantly over the years since the work of [5] and [6], as a result of new observations. With a longer observational arc available, the orbit of 2001 QR₃₂₂ had become better constrained, with orbital elements that had shifted significantly from the original studies. We decided to see whether the new orbit remained dynamically stable.

To do this, we carried out detailed n -body dynamical simulations of the new orbit ([15]), and found that the new solution was balanced precariously between regions of dynamical stability and instability. In our simulations, test particles located at a semi-major axis greater than 30.30 au were found to be significantly less stable than those at smaller semi-major axes. The nominal best-fit solution for the semi-major axis of 2001 QR₃₂₂ at the time of that work lay at 30.3023 au, right at the very inner edge of the unstable region.

In our simulations, half of the test particles considered were removed from the Solar system within just 590 Myr – a period far shorter than the system’s age, but not so short that it did not remain feasible that 2001 QR₃₂₂ had formed in the Neptune Trojan cloud, or had been captured during that planet’s migration, in the Solar system’s youth. Given the sharp delineation between regions with greatly differing stability, our results highlighted the critical importance of further follow-up observations of 2001 QR₃₂₂, to better constrain the objects orbit and to help resolve on which side of the dynamical divide it actually lies.

In this work we present the preliminary results of a fresh study of 2001 QR₃₂₂'s dynamical stability, based on an updated orbital solution published on the Asteroids Dynamics Site (AstDyS; [16]) website in January 2014. In the next section we describe the set-up of our new simulations, before presenting our preliminary results. We then conclude with a discussion of those results, and of the future work we plan to undertake.

The Simulations

In order to study the stability of the orbit of 2001 QR₃₂₂, we took the best-fit orbital solution from the Asteroids Dynamic Site, AstDyS ([16]) on 24th January 2014. The full solution, with uncertainties, is given in Table 1. For comparison, we also present the orbital elements used in our previous work, given in red italicised text, as obtained on 26th January 2009 from the same website. Whilst the uncertainty on the semi-major axis, a , has increased slightly, the uncertainties of the other elements have dropped by a factor of ~ 2 . We note, also, that the value of some elements has changed by significantly more than their original uncertainties¹. Taken in concert, this highlights the critical importance of follow-up observations for Solar system objects – by extending the observational arc over which an object has been followed, its orbit can be greatly refined.

| Element | Value | 1- σ uncertainty ² |
|--------------|-----------------------------|--------------------------------------|
| a (au) | 30.2848 <i>30.3023</i> | 0.009292 <i>0.008813</i> |
| e | 0.027298 <i>0.031121</i> | 0.0001605 <i>0.0003059</i> |
| i (°) | 1.322 <i>1.323</i> | 0.0005654 <i>0.0009417</i> |
| Ω (°) | 151.599 <i>151.628</i> | 0.01484 <i>0.02328</i> |
| ω (°) | 163.415 <i>160.73</i> | 0.4789 <i>0.8316</i> |
| M (°) | 66.336 <i>57.883</i> | 0.4753 <i>0.7818</i> |
| Epoch (JD) | 2456600 <i>2454800</i> | |

Table 1: The best-fit orbital elements, and their associated 1- σ uncertainties, for 2001 QR₃₂₂. The values given in black are those used in the current work, and were obtained from [16] on 24th January 2014. The values given in red italics are those used in our previous work ([15]), obtained from [16] on 26th January 2009, and are included here to show how the best-fit solution has changed as a result of new observations being made. Here, a is the semi-major axis, e the eccentricity, i the inclination, Ω the longitude of the ascending node, ω the longitude of perihelion and M the mean anomaly of 2001 QR₃₂₂ at the epoch given in the final row.

¹ The value of the semi-major axis, for example, has changed by 0.0175 au, a shift of twice the stated uncertainty in the 2009 values. The changes in M and ω are even more striking – with their values shifting many times the stated 2009 uncertainties.

² We note, here, that the values presented in this table, and used in our work, are the precise values as taken from the AstDyS system. It is readily apparent that the uncertainties in a given value (column 3) stretch to significantly more significant figures than given for the ‘best fit’ value (column 2). Whilst this is not ideal, we felt it best to exactly reproduce the data as taken from the AstDyS website, to ensure reproducibility of our results.

To study the long-term stability of the orbit of 2001 QR₃₂₂, we used the Hybrid integrator within the n -body dynamics package MERCURY ([17]) to follow the orbital evolution of an ensemble of massless test particles under the gravitational influence of the four giant planets for a period of four billion years. This technique (following the long term evolution of many objects using MERCURY) has proved highly successful in determining the dynamical stability of objects in our own Solar system (e.g. [15][18][19]). It has also been used to probe questions in astrobiology (e.g. [20][21][22][23]) and exoplanetary science (e.g. [24][25][26]). It allows the chaotic orbital evolution of the objects in question to be quantified in a probabilistic sense, as well as enabling the creation of stability maps that allow the behaviour as a function of initial orbital elements to be examined.

As in our earlier work, we created an ensemble of clones of 2001 QR₃₂₂ for our integrations, centred on the nominal best-fit orbit. The clones were spread across the full $\pm 3\sigma$ uncertainty range for each of the six orbital elements considered. In our earlier studies of both Solar system objects (e.g. [27][28]) and exoplanetary systems (e.g. [25][26]), we have found that the orbital semi-major axis and eccentricity of objects typically play by far the most important role in determining their long-term stability – a fact that was clearly demonstrated in our earlier studies of 2001 QR₃₂₂ ([15]). For that reason we constructed our ensemble to maximise our resolution in these orbital elements. We tested a total of 51 unique values of semi-major axis, distributed evenly across the full $\pm 3\sigma$ uncertainty range. At each of these semi-major axes, we tested 51 unique eccentricities, again evenly spread across the full $\pm 3\sigma$ uncertainty range in that element. At each of these locations in a - e space, we tested five discrete values of inclination, and three unique values of the longitudes of perihelion and ascending node, and three mean anomalies, each spread evenly over the full $\pm 3\sigma$ uncertainty range³. In total, this produced a test sample of 351,135 test particles ($51 \times 51 \times 5 \times 3 \times 3 \times 3$).

The orbits of these test particles were then integrated forward in time under the gravitational influence of the four giant planets, Jupiter, Saturn, Uranus and Neptune, with an integration time-step of 120 days. Objects were removed from the simulations when they collided with one of the giant planets, fell into the central body, or were ejected to a barycentric distance of 1000 au, as in our previous studies of the Neptunian and Jovian Trojans ([15][18][27][28]). When objects were removed in this manner, the time at which the ejection or collision occurred was recorded.

Preliminary Results

Of the 351,135 clones of 2001 QR₃₂₂ integrated in this work, 99,949 survived for the full four billion years of the integrations (a 28.46% survival rate). During the first few million years of the simulations, no ejections or collisions occurred – with the first test particle to be removed coming after 3.66 million years. After this slow start, the decay began to proceed apace, with fully half the test particles being removed in the first 600 million years. By recording the time at which each test particle was removed, we are able to create a dynamical map that illustrates how the stability of 2001 QR₃₂₂ depends on its initial orbit, as can be seen in Figure 1, below. Equally, one can plot the decay of the number of test particles as a function of time, as can be seen in Figure 2.

³ We therefore tested the best-fit inclination value along with four others, located -3σ , -1.5σ , $+1.5\sigma$ and $+3\sigma$ from that value. For longitude of perihelion, ascending node, and mean anomaly, we therefore tested the best-fit values along with those $+3\sigma$ and -3σ away.

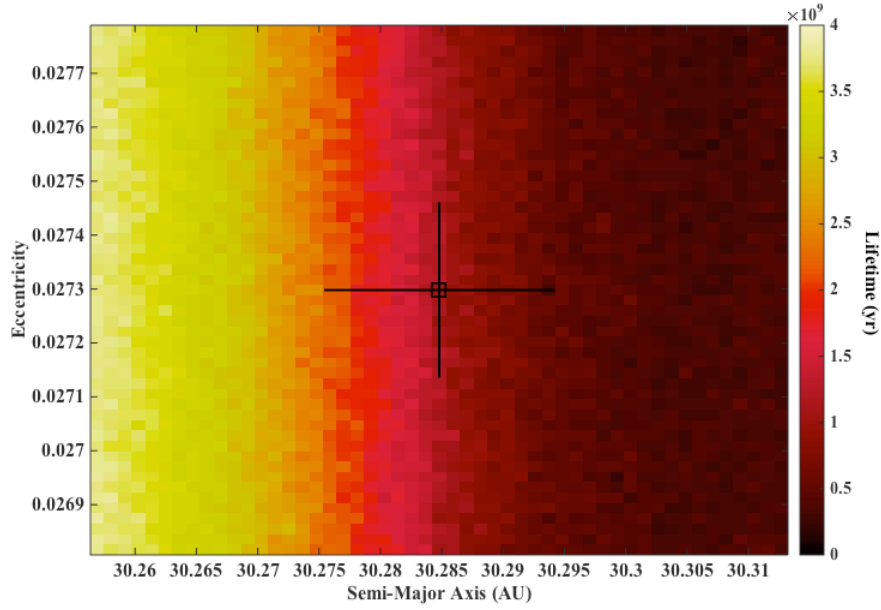


Figure 1: The mean dynamical lifetime of the orbit of 2001 QR₃₂₂ as a function of its initial semi-major axis and eccentricity. The nominal best-fit orbit lies at the centre of the plot, within the small hollow box, and the horizontal and vertical lines that radiate from it represent the 1- σ uncertainties in semi-major axis and eccentricity. The lifetime plotted at each a - e location is the mean of 135 discrete simulations. It is clear that the best-fit orbital solution for 2001 QR₃₂₂ falls right on the boundary between a region of high stability and one that is far more chaotic.

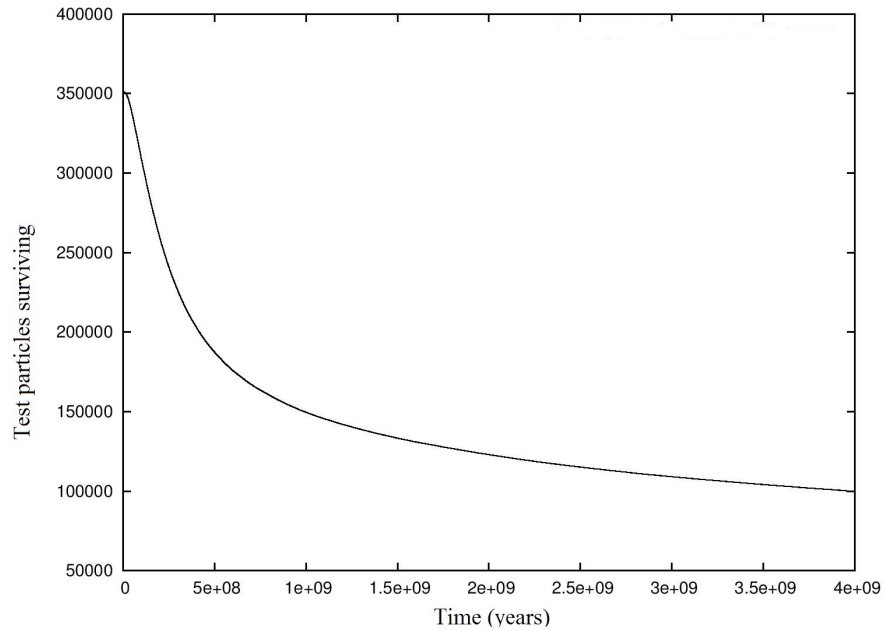


Figure 2: The number of test particles surviving as a function of the time elapsed in our simulations. After a short period of dynamical relaxation (the first particle removed survived for 3.66 Myr), the population decays in a broadly exponential manner, although the ‘half-life’ of that exponential decay increases as time passes, as the objects from the least stable reaches of a - e space are removed.

Discussion and Conclusions

In our previous study of the stability of 2001 QR₃₂₂ ([15]), we examined the evolution of an ensemble of 19,683 test particles, cloned in a six-dimensional swarm centred on the nominal best-fit orbit available at the time. That work revealed an object balanced on a dynamical precipice – right on the boundary between stable and unstable regions.

With a more refined orbit, based on a longer observational arc, we anticipated that new simulations could answer the question of 2001 QR₃₂₂'s stability. On one hand, the best-fit solution might have moved to a more stable region of orbital element space, and we could therefore conclude that 2001 QR₃₂₂ was most likely captured as a Neptune Trojan in the final stages of planetary migration (e.g. [12]), or had formed with the planet and been carried along with it as the planet migrated to its current resting place (e.g. [11]). On the other, it was equally possible that the improved orbit for 2001 QR₃₂₂ could place it firmly in an unstable region – suggesting that it might only recently have been captured as a Neptunian Trojan (as is thought to be the case for 2004 KV₁₈; [28]).

In this work we expand upon our previous study of 2001 QR₃₂₂, taking advantage of the greatly increased computational capacity available to us. We simulated a population of test particles more than an order of magnitude larger than in our previous work, and followed their evolution for a factor of four times longer (4 Gyr vs. 1 Gyr). This has allowed us to increase the resolution with which we can map the dynamical stability of 2001 QR₃₂₂'s orbit, as well as allowing us to probe cases where the instability occurs on timescales longer than those considered in our earlier work.

Whilst our detailed analysis of the results is still ongoing, it is immediately apparent from examination of Figure 1 that the stability of 2001 QR₃₂₂ remains strongly dependent on the initial semi-major axis of its orbit. Despite the longer observational arc and generally smaller uncertainties in the best-fit orbit, that solution remains precariously balanced between regions of significant dynamical stability and instability. As in our earlier work, fully half of the test particles considered were removed from the Solar system within the first 600 Myr of our simulations. Indeed, despite the changes to the orbital solution, our results are remarkably similar to those we obtained in 2010.

Our simulations reveal that all $a-e$ locations within the $1-\sigma$ uncertainties are unstable on timescales less than ~ 2 Gyr, which in turn suggests that the object is truly dynamically unstable. That said, it should be noted that instability on timescales of hundreds of millions of years, or several billion years, is not incompatible with the idea that 2001 QR₃₂₂ has been trapped in the Neptunian Trojan cloud since the cessation of planetary migration (as discussed in [15]).

To illustrate this point, let us assume, for the sake of argument, that the initial population of the Neptunian Trojan cloud was large⁴, and then assume that a non-negligible subset of that population moved on orbits similar to that of 2001 QR₃₂₂. In such a scenario, it is readily apparent that a significant population of such objects could survive to the current day. For a population decaying with a dynamical ‘half-life’ of 600 Myr, $\sim 1\%$ would be expected to survive for four billion years. Furthermore, as we argued in [30], such a scenario would allow

⁴ This seems a reasonable assumption, given that estimates of the *current* Neptunian Trojan population have ranged as high as 10^7 objects more than 1 km in diameter (e.g. [29]).

the Neptunian Trojans to act as a continual source of fresh material to the Centaur population, and from there, to the inner Solar system⁵.

Given that objects escaped from the Neptunian Trojan cloud at all locations plotted in Figure 1, it is clear that even the most stable orbital solutions for 2001 QR₃₂₂ do not preclude its eventual escape to the Centaur population. We still require the orbit of 2001 QR₃₂₂ to be further constrained before we can conclusively determine its true stability.

To that end we plan to obtain follow-up observations of 2001 QR₃₂₂ in 2016, with the goal of further refining the best-fit solution to its orbit, and hopefully answering the question of its true dynamical stability, once and for all.

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⁵ The Centaurs are the direct parent population to the short-period comets (e.g. [31][32]), and are likely themselves sourced from a variety of regions, including the Scattered Disk (e.g. [33]), the Oort Cloud (e.g. [34][35]), and the Jovian and Neptunian Trojan clouds (e.g. [30]).

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